GIXUVR - Grazing Incidence Extreme Ultraviolet Reflectometry: an All-Optical Technique for Metrology of Ultra-Thin Layers

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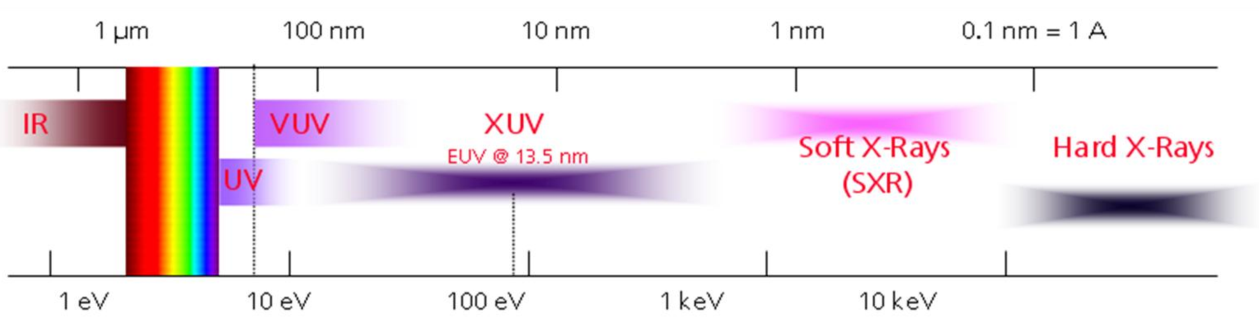
In order to miniaturize today's metal oxide semiconductor field effect transistors even further, channel lengths and gate dielectric thicknesses need to decrease. Traditionally deployed SiO_2 dielectrics face serious difficulties due to rising leakage currents and need to be replaced by alternative (high-k) materials with a larger dielectric permittivity and equivalent oxide thickness in the future. A current focus of the industry is centered on thin films of HfO_2 as a promising candidate for further scaling of such devices. Characterization of these layered systems is mandatory to measure and control the interface between substrate and high-k material as it can severely influence its electric properties. Here we propose a novel metrology technique, namely Grazing Incidence Extreme Ultraviolet Reflectometry (GIXUVR), utilizing short wavelength radiation from off-synchrotron sources for the analysis of such thin-film structures. Benefits of the method are the rapid measuring time (on the order of milliseconds to seconds) as well as high thickness, density and material sensitivity due to the very efficient interaction of extreme ultraviolet light (XUV, 1-50 nm, or EUV, at about 13.5 nm) with matter.

Extreme Ultraviolet Radiation



short wavelength ⇔	good lateral resolution ⇔	microscopy, structuring
strong interaction with matter ⇔	short $L_{penetration}$ ⇔	surface analysis, reflectometry
ionizing radiation ⇔	photochemical properties ⇔	lithography, spectroscopy

- refractive index close to unity
- all materials highly absorptive
- low penetration depths
- HV conditions necessary
- surfaces highly reflective for XUV under grazing incidence

refractive index:

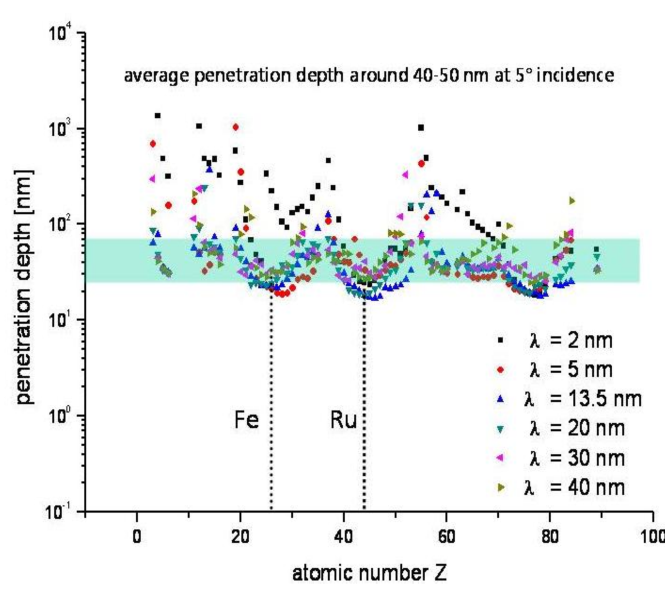
$$n = 1 - \delta + i\beta$$

$$\delta = \frac{r_e \lambda^2 N_A \rho}{2\pi M} f_1^0(\omega)$$

$$\beta = \frac{r_e \lambda^2 N_A \rho}{2\pi M} f_2^0(\omega)$$

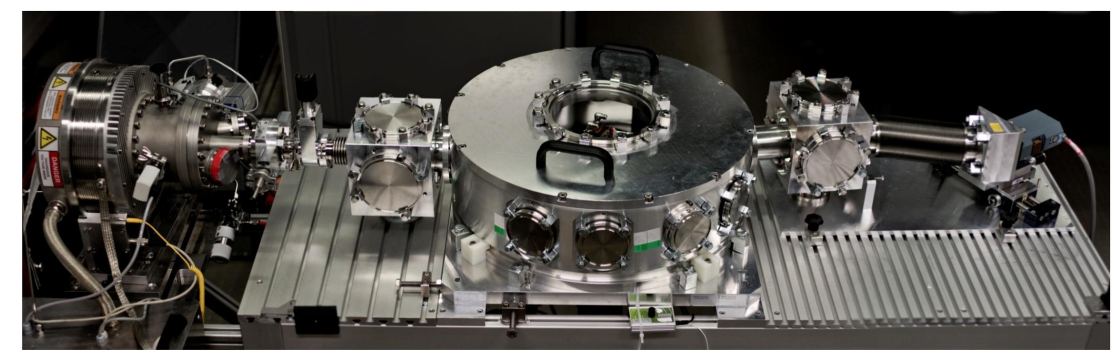
atomic scattering factor:

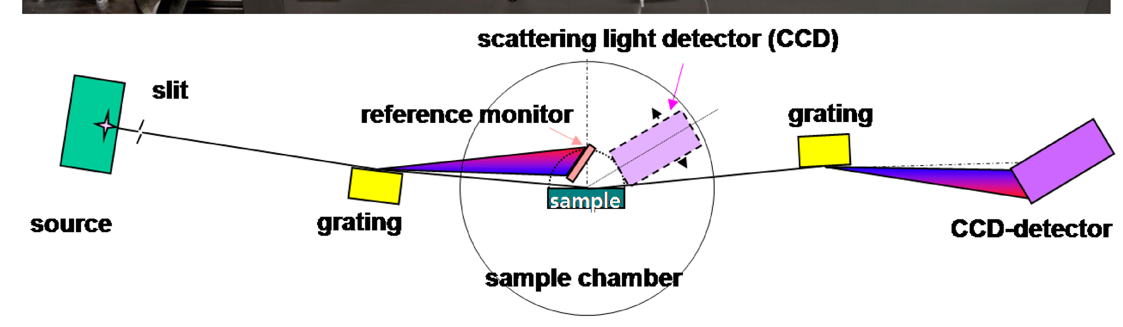
$$f_1^0 - i f_2^0 = \sum_{s=1}^{Z} \frac{\omega^2}{\omega^2 - \omega_s^2 + i\gamma\omega}$$

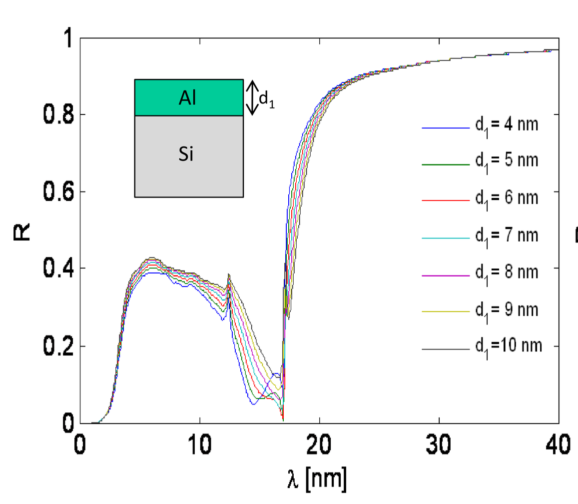


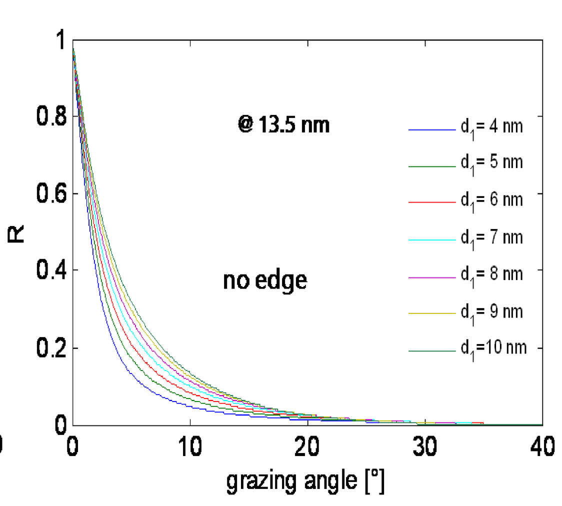
XUV Reflectometry

- first demonstrator build based on a discharge produced plasma source
- Xe spectrum offers quasi continuum for 10 – 20 nm
- polychromatic approach







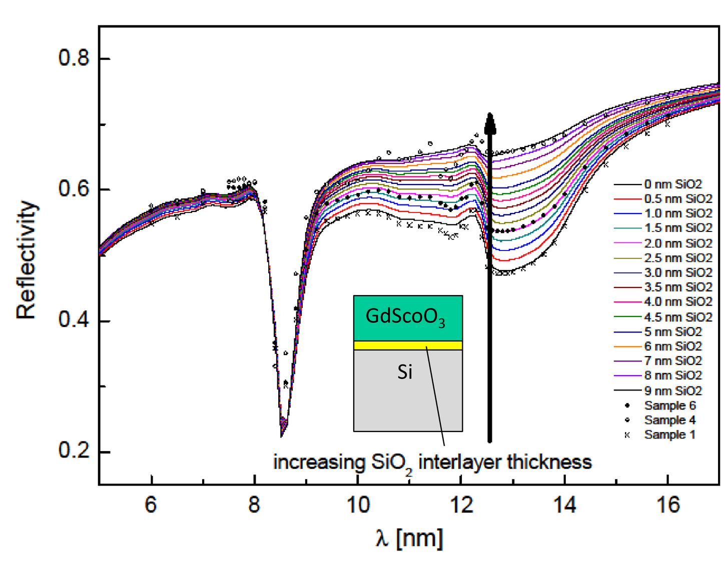


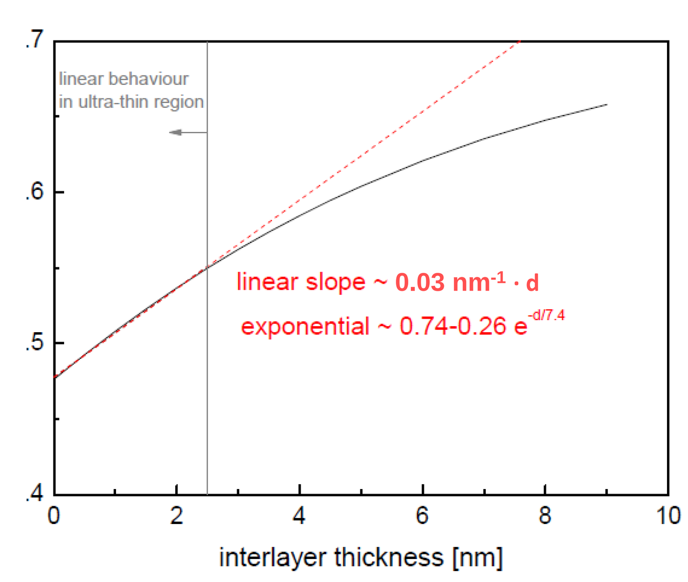
- high surface sensitivity, thickness / roughness / material dependence
- absorption edges of materials accessible (e.g., Si @ 12.4 nm, Al @ 17 nm)

Application: Analysis of Ultra-Thin Layers in High-k Gate Dielectric Stacks

Proof-of-Principle Investigations at PTB, BESSY II

- $GdScO_3$ gate stack with differing „parasitic" oxide thickness
  Investigations carried out in collaboration with J. Schubert (FZJ IBN-1)

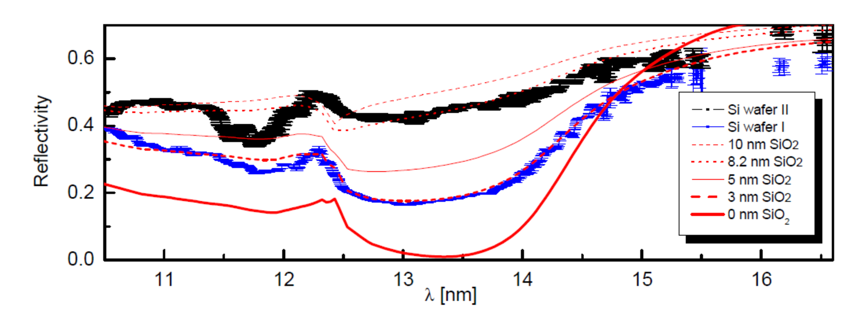


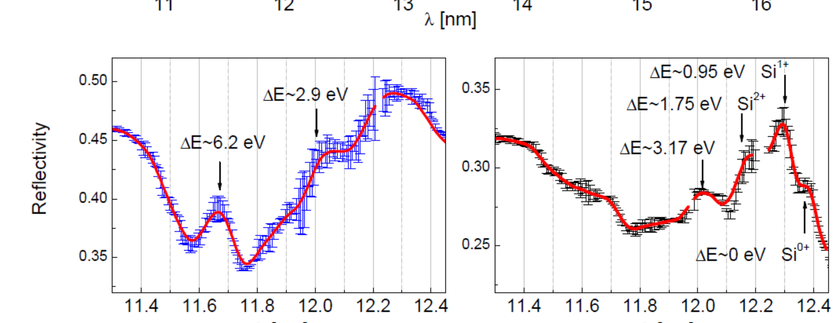


- high contrast for buried ultra-thin interlayer (thickness high-k: 5 nm)
- difficult to access with other all-optical (non-destructive) methods
- characteristic NEXAFS fingerprint at Si L-edge (12.4 nm) visible

Characterization of Ultra-Thin Oxides on Wafers

- laboratory GIXUVR investigation of natural / thermally grown oxides

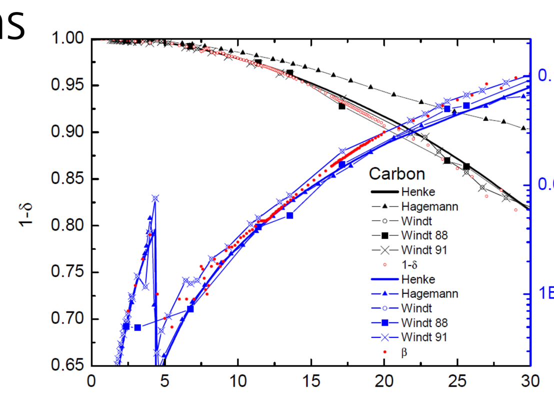




- high thickness contrast in ultra-thin range (< 10 nm)
- NEXAFS reveals difference between natural and thermally grown oxide
- structures can be attributed to intermediate oxidation states
- "fingerprint" database needed for interpretations

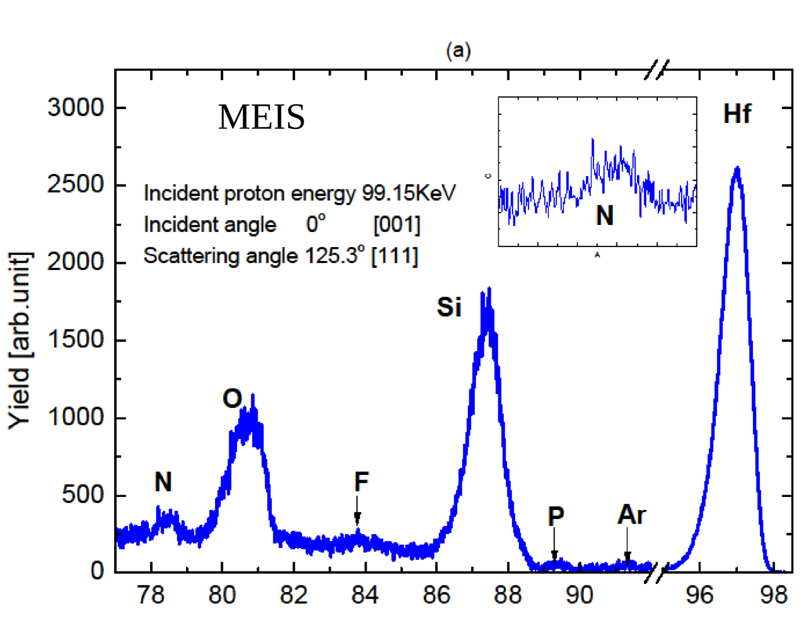
Database build-up for relevant materials

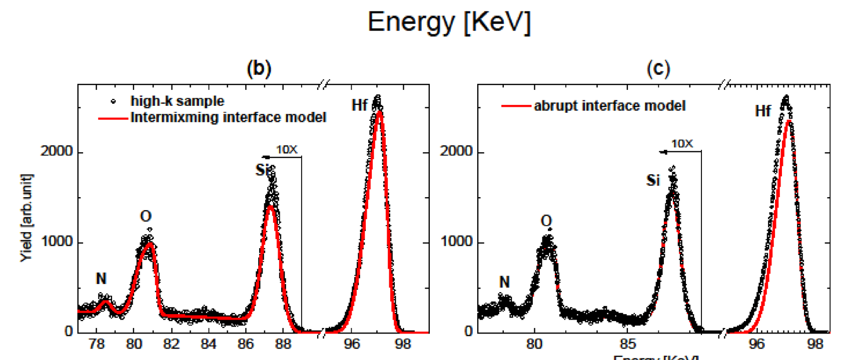
- refractive index ($n = 1 - \delta + i\beta$) determination in XUV from multi-angle reflectivity measurements

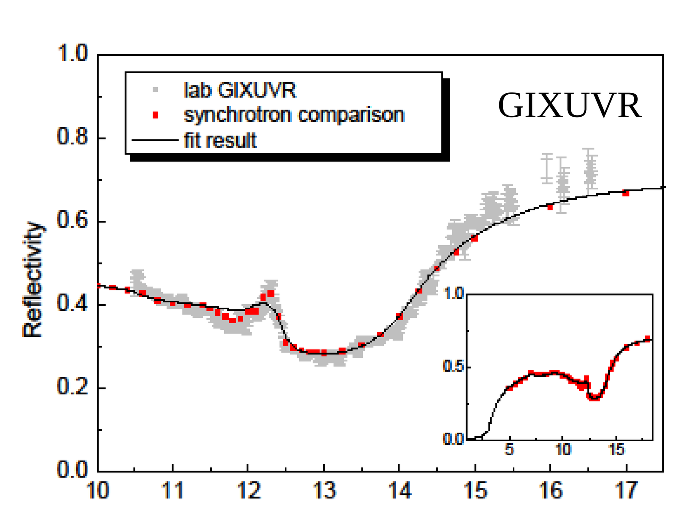


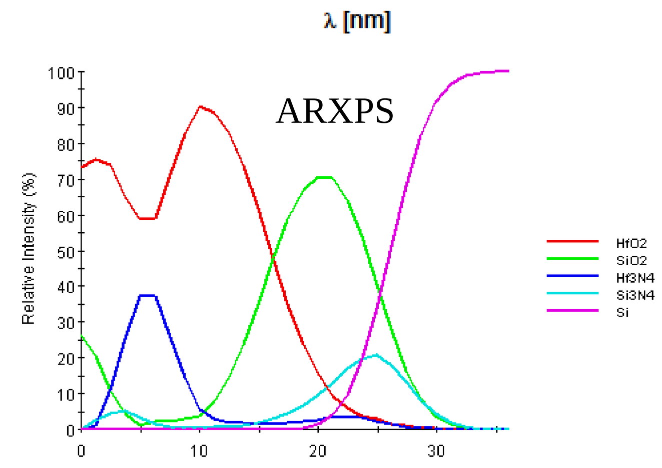
Cross-characterization of a HfO_2 gate dielectric stack

- Investigation of a typical HfO_2 MOS structure by GIXUVR, ARXPS and MEIS in collaboration with M. Liehr et. al. (CNSE Albany, USA)









- MEIS: majority of N (~75%) incorporated into HfO_2 layer, likely presence of Hf_3N_4
- ARXPS: nitrogen presence confirmed, diffusion near to the substrate, interdiffuseness ~0.5 nm
- GIXUVR: agreement with ARXPS results, deviations from bulk densities required to generate best fit

Benchmarking of techniques

	MEIS	ARXPS	GIXUVR
In	Ion	Photon	Photon
Out	Ion	Electron	Photon
Typ. Depth of Analysis	1 µm	1-10 nm	1-100 nm
Typ. Spatial Resolution	1 mm	> 50 µm	µm-mm
Typ. Measuring Time	Min-hours	hours	ms-s
Required Vacuum Level	10^{-6}-10^{-9} mbar	10^{-6}-10^{-9} mbar	10^{-2}- 10^{-5} mbar
Determined Layer model	(5Å)HfO_2/(3Å)$HfO_2N_{1.5}$/(3Å)$HfSi_{2.4}O_4N$/(9Å)$HfSi_2O_4$/(3Å)SiO_2/Si	(5Å)Hf_3N_4/(9.6Å)HfO_2/(10.4Å)SiO_2/(7.9 Å)Si_3N_4/Si {(3Å)HfO_2/(5Å)HfON/(7Å)HfO_2/(7Å)SiO_2/(6Å)SiON/Si}	(5.1Å)Hf_3N_4/(9.7Å)HfO_2/(10.0Å)SiO_2/(8.3Å)Si_3N_4/Si
Strength for high-k analysis	Even slight residuals / dopants / contaminants noticeable and identifiable (pure elements)	Detailed depth profile including the interfaces visualizing diffuseness of e.g. nitride into the stack	density sensitive, fast measuring times, NEXAFS fingerprint of interface
Weakness for high-k analysis	partly destructive for the surface due to ion bombardment, model dependent layer parameters	very long measuring times, limited depth of analysis if significant layers are buried even deeper, model dependent layer parameters	Layer parameters are model dependent, limited NEXAFS database

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